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Original Article

Performance Evaluation of Pavement Quality Concrete with Wood Powder: A Finite Element Modelling and Economic Exploration

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Abstract *- Nowadays, research has increasingly focused on alternative additives that enhance the sustainable performance of Pavement Quality Concrete (PQC), enhanced by the growing demand for eco-friendly pavement materials. This study explores the viability of using wood powder as an Internal Curing (IC) agent in PQC through FEM modelling by using the experimental results obtained. From the laboratory experimental results, only the optimum replacement level of wood powder (9.6%) in IC concrete mixes (i.e., IC-9.6% and IC-9.6% ALC 20%) as a partial replacement of fine aggregate is considered and compared with conventionally cured concrete mixes. Fresh properties such as slump, mechanical properties including compressive strength and flexural strength, and durability properties such as density and sorptivity of these mixes are discussed, along with correlation graphs of the results. The micro investigation, such as FESEM, is also discussed to verify the results obtained. These results are then used for pavement modelling (FEM Modelling) for single axle load (i.e., 10.2 tons) to forecast structural reactions and service life enhancements with the amended concrete mix. Fatigue life of pavement on the basis of stress ratio was calculated, and an economic analysis is also done to estimate the life cycle cost of wood powder-modified PQC with those of traditional mixes. The study's conclusions show that employing wood powder as an IC agent in pavement construction offers an economical and eco-friendly way to improve infrastructure performance. It also has the added advantage of lowering water waste through ready-made curing processes in the world of water scarcity.*

Keywords *- Economic evaluation, Finite element modelling, Internal curing, Pavement quality concrete, Wood powder.*

1. Introduction

Concrete strength development depends majorly upon the hydration of Cement. "Studies have shown that once the relative humidity within the capillary drops below 80%, hydration virtually stops" [1]. "Concrete mixtures having w/c ratio less than approx 0.50 and sealed against moisture can't develop their full potential hydration due to lack of water. It needs water for full potential hydration" [1]. Curing operations ensure that adequate amounts of water and temperature conditions are available for cement hydration to occur. Curing can be done in two ways -

1. External curing
2. Internal curing

"External curing refers to the process of maintaining adequate moisture and temperature in freshly placed concrete after placement and finishing by external means to ensure continuous hydration of cement and the development of desirable microstructural and mechanical properties" [2]. Unlike internal curing, which supplies water from within the mix via pre-saturated materials, external curing relies on surface moisture retention or additional water supply from external sources, as shown in Figure 1.

The cement hydration is a chemical reaction that requires both water and suitable temperature conditions. Premature evaporation of water from the surface can slow or even halt hydration, resulting in incomplete cement reaction, higher porosity, reduced strength, and increased susceptibility to shrinkage cracking [3].

Internal-curing is also known as self-curing. The ACI-308 Code states that "internal curing refers to the process by which the hydration of cement occurs because of the availability of additional internal water that is not part of the mixing Water" [4]. The American Concrete Institute (ACI) defined internal curing in 2010 as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation." [5].

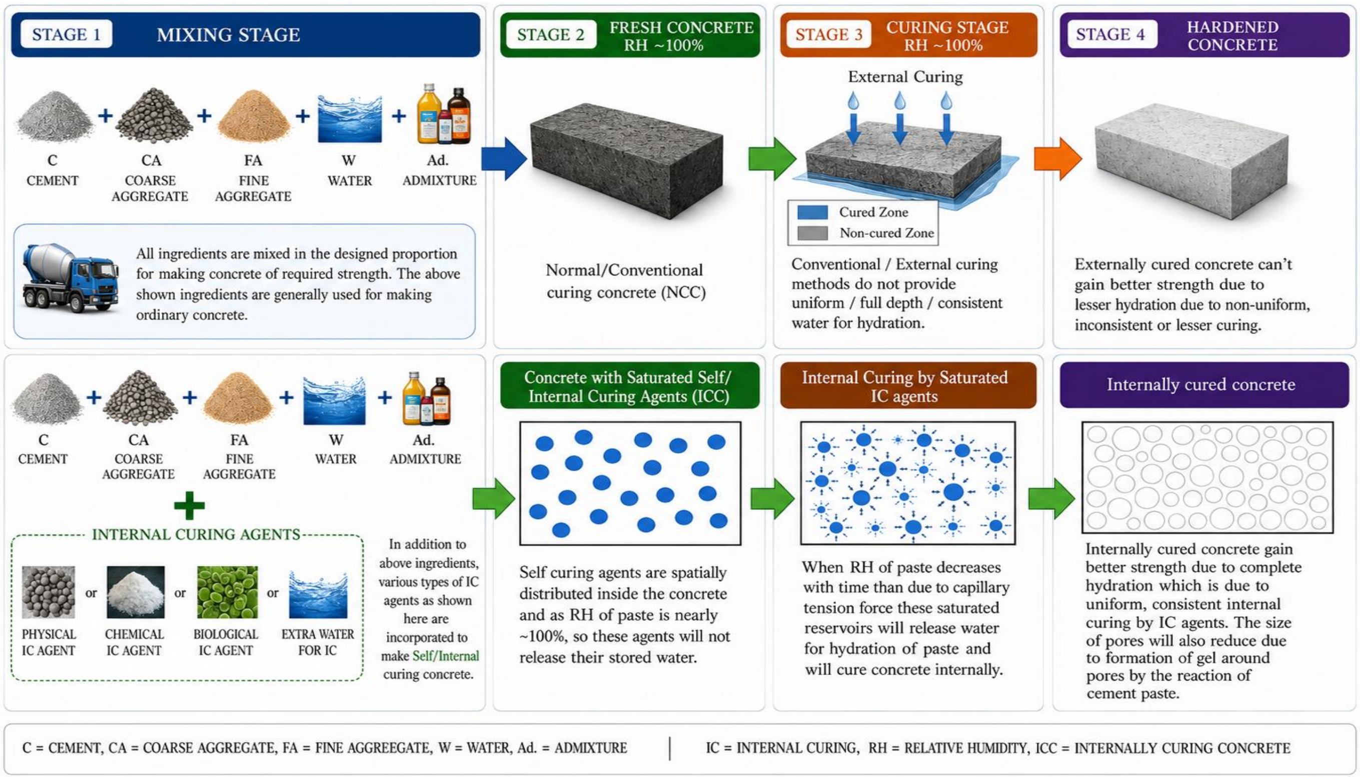

Fig. 1 Difference between external curing and internal curing

1.1. Limitations of External Curing

- A lot of water is wasted in external curing, which can be saved by using self-curing agents.
- High-Performance Concrete (HPC) pavement's lower permeability makes uniform distribution of water more difficult in slab by external curing.
- Concrete mix design for pavement construction requires a lower w/b ratio, less ≤ 0.36, for obtaining high mechanical. Strength and elastic modulus, which results in high self -desiccation and finally cracking as shown in Figure 2. "Wei and Hansen have observed that during a drying time of 16 d, warping was reduced by 70 % by incorporating internal curing into a w/c=0.45 concrete" [6].

Fig. 2 Shrinkage crack in concrete, closer look [7]

Concrete mixtures with a water/cement ratio (w/cm) below 0.35 is suitable for the rigid pavements due to higher mechanical strength gain [2, 8]. At such low w/cm ratios, the present water inside the matrix may not be enough to fully hydrate the mix, which can promote drying the inner matrix and lead to shrinkage. "Additionally, these types of mixes uses Supplementary Cementitious Materials (SCMs) such as pulverized fuel ash, ground granulated blast furnace slag and which often require extended curing to ensure proper reaction within the cementitious system. Some SCMs, due to their high surface area and reactivity, can further increase self-desiccation and chemical shrinkage during hydration because of their extra demand of water in low w/cm mixtures" [9]. This extra demand of water can only be fulfilled by providing water through curing only. As the High-Performance Concrete (HPC) has very low permeability, which can hamper the penetration of curing water supplied by the external means, even at early ages also.

In 1998, the American concrete institute committee report 363 said, "Even with proper curing practices, external water might not reach unhydrated cement grains, limiting further cement hydration and SCM reactions. Because pavement construction exposes large areas of concrete to drying, extended moist curing of HPC pavements is critical to ensure adequate early and long-term performance. Without sufficient curing, issues such as plastic shrinkage, thermal shrinkage, drying shrinkage, slab warping, cracking, and generally poor performance can occur. Recent research has focused on incorporating materials like Superabsorbent Polymers (SAPs) and lightweight aggregates to provide internally stored water for self-curing and reduce shrinkage in HPC" [10, 11]. "Providing internal water storage in HPC for rigid pavements can improve resistance to drying, shrinkage, and cracking. In the high-performance concrete now being used, capillary porosity becomes disconnected during the first few days of hydration" [12]. In the construction process of civil engineering structures, the fabrication of 1 m^3 of concrete requires approximately 3 m^3 of water, with the maximum share of this volume dedicated for the curing process [13]. Water-scarce regions are increasing, and water loss is higher with external curing methods. For example, in 2019, Chennai experienced a severe water crisis that impacted the construction industry, forcing companies to purchase tanker water and increasing construction costs [14]. So the internal curing concept emerges out as a need of hour for fulfilling the water demand of the construction industry.

1.2. Case studies of using internal curing concept field applications

The field application of internal curing concept from laboratory environments to widespread implementation within U.S. transportation infrastructure, Denver water tanks, Bridge decks. "A seminal case study is provided by the Indiana Department of Transportation's 2013 installation of 4 IC high-performance concrete bridge decks, which achieved an 80% reduction in early-age autogenous shrinkage and a projected service life increase of more than 3 times compared to conventional mixtures" [15]. Di Bella's evaluation of instrumented bridge decks in Monroe County, which observed diminished thermal stress, restrained strain, and cracking propensity, alongside improved chloride-ion resistance, all while maintaining equivalent compressive strengths [16]. Furthermore, work by Cleary and Delatte for the Ohio DOT confirms these results [17]. Denver (U.S.) supplying water to its surrounding since 1930. Colorado's very dry, desert-like climate makes constructing large capacity, monolithically placed water storage tank slabs a complex proposition. To hold water, Denver water needs a tank with longer life (approx. 100 years) without leaking. For meeting the criteria, Holcim (US) experts used ICC mix with prewetted expanded shale aggregates as an internal curing agent and constructed water storage tank in 2012 [18].

The use of wood powder or sawdust in concrete as a partial replacement for cement or sand has been investigated for over four decades to enhance sustainability while maintaining structural integrity. Wood powder, also referred to as sawdust, is a fine, fibrous byproduct generated during woodworking operations such as cutting, sawing, grinding, and sanding of timber. It consists primarily of small lignocellulosic particles and is commonly produced in large volumes by sawmills, furniture factories, and carpentry workshops. Sawdust is a widely available byproduct in the timber industry and is often less utilized or disposed of with minimal economic benefit [19]. In many tropical and developing regions, sawdust is abundant and economically accessible, making it a suitable material for sustainable construction applications.

Wood powder came mainly into limelight in the 19th century. In India, wood powder was used mostly in the production of toys, furniture, and other similar light household items. Moreover, thermal industries use a substantial quantity of wood powder as loose biomass fuel during combustion processes for generating thermal energy. However, it is very much important to note that this practice poses significant environmental risks, ultimately impacting human health. The Indian timber market is experiencing rapid growth day by day, and a major byproduct of wood processing in this industry is wood powder, which is generated in substantial quantities.

According to data provided by the American Hardwood Export Council in 2016, "India had approximately 23,000 sawmills, with each sawmill producing an average of about 822.4 tons of wood powder annually. An analysis of this data reveals that India generates approximately 18.91 million tons of wood powder each year. In India approx. 5.5 million tons of surplus wood powder is produced yearly" [20]. This volume, if converted to million m^3, comes out to be 26.19 million m^3 annually (density of wood powder is approximately 210 kg/ m^3 [21]. [22] Recommended using sawdust particles that proper sieving through a 6 mm sieve to achieve consistency in performance and helps avoid issues such as poor workability or strength reduction due to oversized or irregular particles. Furthermore, pre-treatment of sawdust, such as drying, grading, and sometimes partial carbonation, may be necessary to reduce the risk of organic degradation or excessive absorption, which could otherwise affect the setting and strength gain of the concrete mixes.

A major byproduct of wood processing in this industry is sawdust, which is generated in substantial quantities. According to data provided by the American Hardwood Export Council in 2016, "India had approximately 23,000 sawmills, with each sawmill producing an average of about 822.4 tons of sawdust annually". With the passage of time, the generally ignored phase of construction has become so important. This has become possible due to intense research carried out over a period of time on the subject. Early investigations into cement compatibility with wood-based materials were carried out by [23] and later by [24], who explored the influence of wood extractives and species on hydration behavior. They demonstrated that wood can interfere with cement hydration unless properly treated. Parallel studies by [25] reviewed the chemical interactions and pre-treatment methods that improve the performance of wood–cement composites.

Although these above discussed studies did not completely focus on internal curing, but they laid the base for understanding the behavior of wood in cementitious systems. [26] Further contributed by analyzing lignocellulosic waste and its integration into concrete. These early works established that treated and optimized wood particles can enhance moisture retention and dimensional stability in cement-based materials. [27] Formally introduced the concept of ic by defining the idea of protected paste volume using pre-saturated lightweight aggregates. In the starting of 2000s, research mainly turned toward using organic waste materials as fine aggregate replacements or pozzolans. [28] Combined limestone and wood powder waste to develop lightweight construction materials. In this study, he used 10 to 30% of the mix with wood lime and achieved a reduction in unit weight of 65% while maintaining compressive and flexural strength levels. This study highlighted wood powder's potential for lightweight and cost-effective applications. [29, 30] advanced the research by testing rigid pavement concrete with varying mix ratios of 1:1:2 to 1:4:8 and concluded that up to 10% wood powder replacement maintained the compressive strength necessary for pavement use, 18.35 N/mm² at 28 days and flexural strength of 1.71 N/mm², which is above the minimum threshold value for structural applications, marking the importance of controlled replacement ratios.

[31] Examined replacement levels of 5% is optimum to study wood powder's impact on mechanical performance and thermal insulation. [32] Further expanded this research by replacing sand with wood powder's increment up to 100%, and found that the workability and compressive strength dropped sharply after a 25% replacement, which confirms that the higher substitutions weakened structural integrity and performance. [32, 33] also demonstrated that partial replacements from 10% to 25% can meet the strength while giving cost benefits. [34] Tested wood powder's substitution by volume of cement and reported that as the wood powder's proportion increased, workability and density decreased while water absorption rose, highlighting a material degradation.

[35] Were the first among the researchers to explicitly examine wood powder as an ic agent by studying the M30 grade concrete with replacement of 2–8% wood powder and polyethylene glycol (PEG-400) admixtures. They observed that the mix containing 6% wood powder with 1.5% to 2.5% PEG-400 performed best. Reduced shrinkage and enhanced strength under ambient and outdoor curing was observed. [34] Compared mix ratios of 1:1, 1:2, and 1:3 by volume, assessing strength, fire resistance, and Ultrasonic Pulse Velocity (UPV). The 1:1 mix displayed the best performance at 56 days, showing compressive strength of 19.53 MPa and superior fire resistance at temperatures up to 800°C. [35] Later examined the combination of polymer and self-curing concrete, observed improved strength and durability by incorporating wood powder. [36] Found that pre-soaking wood powder can improve the internal curing and microstructural bonding, which further enhances the performance.

[37] Examined the wood ash and powder in marine clay stabilization for internal moisture regulation and strength gain, improved stiffness and microstructural development. [38] Concluded that substituting 3% wood powder in hollow concrete blocks achieved optimal compressive strength with comparable water absorption. The use of pre-wetted wood powder as an internal curing agent by observing the reduced autogenous shrinkage, improved hydration, and enhanced mechanical properties of the mix studied. In this study, the SEM analysis verified the denser CSH gel and lesser micro cracks, confirming the internal curing mechanism. Recent reviews have also focused on composite formulations combining wood powder with Supplementary Cementitious Materials (SCMs). Some research done into nano-treated and chemically modified wood powder has shown improved results.

From above studies, it can be observed that the various studies have examined the application of sawdust (SD) in concrete mixtures, investigating different ratios and their influence on mechanical and thermal properties. Researchers found that a 5% substitution of cement with SD and 5% to 20% substitution of Fine Aggregates (F.A.) with SD generally yielded optimal results, including higher Compressive Strength (CS) and Split Tensile Strength (STS). However, increasing SD ratios reduced concrete density. Some studies introduced additives like metakaolin to enhance bonding. Additionally, fire resistance tests were conducted, with findings favoring the 1:1 cement-SD ratio. Sustainability has become a key motivator. These studies highlighted how integrating wood waste in concrete supports all-around economy goals, reduces landfill burden, and enhances material performance. These findings align wood powder use with green construction practices. Overall, these studies suggest that a 5% SD replacement can be a viable option for lightweight and cost-effective concrete in construction. It has been observed that mainly agent used are lightweight aggregates, PEG and SAP. Higher grade concrete using internal curing concept is lesser explored as compared to normal grades concretes.

1.3. Research Gaps/importance

With only 0.5%-by-cement screening on 100-mm cubes reported in the IC literature, there is currently no standardized mix-proportioning technique for sawdust as any construction-matrix component [21, 39]. The examined literature does not address the long-term durability, fire resistance, structural performance, worker health, or life-cycle cost-effectiveness of sawdust concrete [21]. The limited pavement-relevant sawdust study makes the gap for internal-curing framework, and no research in the literature was found specifically related to use of pre-wetted wood powder as an internal-curing agent inside a rigid-pavement slab.

This Study is centered on the Finite Element Modelling (FEM) and Economic analysis of experimental investigation of internal curing (also referred to as self-curing) of concrete, with a specific focus on the use of pre-wetted wood powder as a replacement for a portion of the fine aggregates. The wood powder is considered here as a type of porous Lightweight Aggregate (LWA) due to its good water-absorbing capacity and potential to slowly release moisture during the hydration process. The concept of internal curing is particularly significant in today's era of water-scarce concrete technology, where the primary objective is to enhance the performance, durability and sustainability of concrete without compromising its strength, water demand, or service life.

2. Experimental Program

A comprehensive experimental program for carrying the study was designed. At first, the basic material testing was done, and design mix was finalized on the basis of results obtained.

2.1. Material Testing

The materials to be used for the experimental work involved in the research work are cement OPC 43, coarse aggregate with a maximum nominal size of 20 mm, crushed sand, admixture and water. These were investigated for their properties by conducting a series of preliminary tests on them. These are explained below.

2.1.1. Cement

Ordinary Portland cement manufactured by Ultratech of 43 grade and Portland Pozzolana Cement are investigated for their properties. The series of tests conducted on cement were according to [40] for OPC 43 and [41] for ppc cement. The various mandatory tests on ultratech-43 grade cement were done in this study, and results obtained were used for the design mix.

2.1.2. Aggregates

The aggregates to be used for experimental work in dissertation work were run through a series of tests in order to determine their physical properties. Generally, two types of aggregates are used in the preparation of concrete, and they are classified on the basis of their size.

Coarse Aggregates

Aggregates having size range from 20mm passing and retaining to 4.75mm, and fine aggregates have a size less than 4.75mm. Sieve analysis of coarse aggregates was done, and results were meeting the Permissible Percent Passing as per [42]. All properties, such as Size analysis, Specific gravity, Water absorption, Abrasion Value, Impact value, were tested as per [43], and a design mix was prepared on the basis of the results obtained.

Fine Aggregates

In this study, crusher sand was used as fine aggregates due to the non-availability of river sand in the nearby locality. Fineness Modulus was found to be 3.206, Specific gravity and water absorption by pycnometer was found 3.525 and 1.32, respectively. Silt content was found 14.44.

2.1.3. Wood Powder

It is also known as sawdust; wood sawdust can be used as a lightweight aggregate in various construction applications. As a lightweight aggregate, it can offer several advantages, including reduced weight, improved thermal insulation, and increased fire resistance. When used as an aggregate in concrete, wood powder can help to reduce the weight of the concrete, making it easier to transport, handle, and install. Additionally, because wood is a natural insulator, it can help to improve the thermal insulation properties of the concrete, which can lead to reduced energy consumption and lower heating and cooling costs.

In these applications, it can help to improve the fire resistance of the material, as well as its acoustic and thermal insulation properties. However, it is important to note that the use of wood powder as a lightweight aggregate may have certain limitations, such as its susceptibility to decay and degradation over time, and its potential impact on the overall durability of the material. As such, it is important to carefully consider the specific application and requirements of the material before using wood powder as a lightweight aggregate.

In this study, wood powder was taken from the nearby wood cutting shop situated on Mahendergarh road, near Gate no. 2, Central University of haryana. Haryana, as shown in figure 3 above. The mostly used timber was from rohida trees, also known as Tecomella undulata.

Fig. 3 Wood powder heave under wood processing machine in wood cutting shop near CUH, Haryana

Rohida is a deciduous and hardwood tree. Its botanical name is Tecomella undulata, and it is a member of the Bignoniaceae family. This tree is also known as “Marwar teak” or “Desert teak” because it produces high-quality wood that is both monetarily useful and good for wood carving art. Rohida is used extensively as a raw material in the wooden industries to make furniture, doors, windows, handicrafts, tool handles, and building materials because of its exceptional mechanical and physical qualities.

Suitability of Wood Powder as an IC Agent

Wood powder was studied experimentally for finding various properties such as sieve analysis, size, and specific gravity, water absorption and desorption behaviour. FESEM study of wood powder for checking its inherent porosity and structure was done. It can be seen from figure 4, given below, that wood powder has a fibrous and porous structure from within.

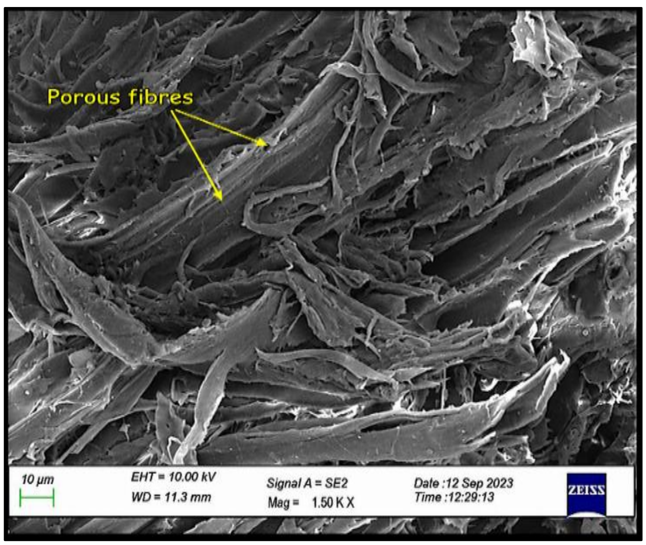

Fig. 4 Show FESEM image of wood powder used in this study

In this series, sieve analysis of wood powder was done, and a size distribution curve of result obtained (shown by blue color line was made, as shown below in figure 5. Size distribution of fine aggregate considered for design mix was also made in same graph for the comparison (shown by brown line). As per size distribution curve, wood powder is comparable to fine aggregate. But it seems finer in size than the fine aggregate considered in this study.

Fig. 1 Show the grain size distribution curve of wood powder and fine aggregates

FTIR Study of Wood Powder

FTIR analysis is a versatile technique that provides valuable information about the chemical composition and molecular structure of materials. FTIR spectroscopy helps identify the determination of the chemical composition functional groups present into the material. In this study, it was found that wood powder contains OH and Phenolic Compounds as shown below in Figure 6, which makes it a potential ic agent [44]. After all material testing of wood powder for the suitability as an ic agent, it was found that it can be used as internal curing due to its high water absorption capacity. Summarized results are given below in table 1

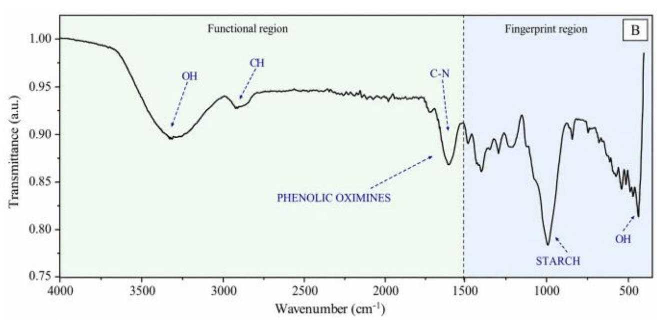

Fig. 2 FTIR integrated graph of wood powder

Table 1 Summarized results of wood powder properties studied

S. no.	Parameter	Experiment conducted	Avg. results	Remarks
1	Size analysis	Sieve analysis	Fineness Modulus =3.25	ZONE IV
2	Specific gravity	Pycnometer	0.40	
3	Water absorption	Pycnometer	203.82%	
4	Water absorption	Mass Method	232.33 %	
5	Chemical composition and molecular structure	FTIR & FESEM	Presence of OH and Phenolic Compounds & Porous fibers	Suitable IC agent

3. Design mix and Laboratory Testing of Concrete

Concrete having M40 grade is a medium- strength mix, which is used in structures such as rigid pavements, bridges, high-rise buildings. Based on the recommendations of IS code [45], the mix proportions of M40 Grade concrete were designed. Table 2 shows the quantities of different materials to be used for M40 concrete in kg/m^3. In the table 2, First column shows the design mix for the conventionally Cured Concrete (cc) mix, while the second column shows the design mix for the Internally Cured Concrete (IC) mix. In this mix, it can be seen that the suitable dosage of an internal curing agent comes out to be 9.6 % with the replacement of fine aggregates.

This dosage is found by the concept of internal curing agent given in IC concrete codes and earlier practice conclusions by different researchers at different ages of their study [46]. The internal curing concept by the Expanded Shale, Clay, and Slate Institute (ESCSI) is based on the "supply = demand" principle given as Equation 1, ensuring that the water stored in pre-wetted lightweight aggregate (LWA) is sufficient to meet the curing water demand of the cement paste as it hydrates.

Supply = demand

$$M_{LWA} \times \phi \times S' \text{ (Supply)} = C_f \times C_s \times \propto_{max} \ (demand) \quad (1)$$

Where:

- M_{LWA}=Mass of lightweight aggregate needed (kg/m³ of concrete)
- S' = Degree of saturation of LWA (as a decimal)
- ϕ=Water absorbed per kg of LWA (kg/kg)/ water absorption capacity (%).
- C_f=Cement Factor(Amount of cement in concrete)
- C_s=The chemical shrinkage of cement (approx. 0.064 ml/g)
- $\propto_{max}$=The expected maximum degree of hydration (0 to 1)

For this study, values as per design mix of conventional concrete is taken as below-

- S' = 1
- ϕ=190.89 %.
- C_f=Cement content+ Fly Ash content=415+90=505 kg/m3
- C_s= 0.07 ml/g)
- $\propto_{max}$= 1

Now putting all values in Equation 2, as shown below -

$$M_{LWA}(oven\ dried\ (OD)\ wt.) = \frac{505 \times 0.07 \times 1}{190.89 \times 1 \times 0.85} = 21.786 \text{ kg}$$

$$M_{LWA}(SSD\ wt.) = M_{LWA}(OD\ wt.)(1 + \phi) \qquad (2)$$

Where: $M_{LWA}(SSD\ wt.)$ = Mass of lightweight aggregate in saturated surface-dry condition**.**

$$=21.786 \text{ kg}(1 + 190.89) = 63.378 \text{ kg/m³ of concrete.}$$

$$M_{LWA} \text{ (SSD wt.) } = 63.378 \text{ kg/m³ of concrete.}$$

Using the above, the required quantity of mass of lightweight aggregate (M_{LWA}), i.e., wood powder, under SSD conditions was determined as 63.378 kg/m³ of concrete. This quantity corresponds to a 9.6% replacement of the fine aggregate by weight, based on the fine aggregate content of 655 kg/m³ in the Conventional Concrete (CC) mix. Therefore, the optimum internally cured concrete mix was designated as IC-9.6**,** representing 9.6% replacement of fine aggregate with wood powder. Three sets of design mixes were developed: Conventionally Cured Concrete (CC), Internally Cured Concrete (IC), and IC mixes with alcoofine. Although only selected mixes First merged column of table 2 shows the design mix for the conventionally Cured Concrete (cc) trial mix, while the second column shows design mix for the Internally Cured Concrete (IC) mix and Third column shows IC mixes with the addition of mineral admixture. Careful procedures were followed during batching, mixing, and casting operations. After casting, all specimens were left in the steel moulds for the first 24 hours under ambient conditions.

Care was taken during demoulding to prevent any damage to the edges, and the specimens were then placed in a curing tank at room temperature for further curing. The room temperature for curing was maintained at 27ºC ± 20ºC, as per [47]. Initial CC trials were optimized for workability and strength, followed by IC mixes replacing fine aggregates at 5.6%, 7.6%, 9.6%, and 11.6% with wood powder, as shown in Figure 7, however which are not shown in this study.

Fig. 7 Photograph of Samples prepared

The 9.6% replacement level was identified as the most effective among all mixes in enhancing curing efficiency without compromising mix stability, verifying the concept of internal curing in earlier practice by different researchers at different ages of their studies [46]. To further improve performance, the IC 9.6 mix was modified using mineral admixtures such as Alccofine (ALC) at 20%. This additions significantly influenced the mix's workability and durability characteristics. Across all mixes, the water-to-cementitious ratio ranged between 0.36 and admixture dosages were adjusted to maintain consistency. It can be seen that the suitable dosage of an internal curing agent comes out to be 9.6 % with the ALC as a mineral admixture.

Table 2. Shows the quantities of each ingredient of design mix in kg/m^3 to be used for M40 concrete

Design Mix for Grade - M40				
S.no.	**Mix constituents**	**CC**	**IC 9.6**	**IC 9.6 ALC 20**
1	Cement	415	415	415
2	Fly Ash	90	90	90
3	Mineral Admixture	-	-	83
3	C.A.(20mm)	655	655	655
4	C.A.(10mm)	560	560	560
5	Sand	655	592	592
6	Water	180	180	178
7	Admixture	8.35	8.35	8.27
8	IC agent	-	63	63
9	total wt./item	2563	2563	2644
10	% IC Agent dosage	0.00	9.68	9.68
11	Admixture Dosage (%)	1.65	1.65	1.66
12	W/C	0.36	0.36	0.36

4. Concrete Testing

For the safety and long-term viability of building projects, concrete testing is crucial for confirming the Fresh state, strength, durability, and quality of concrete structures.

4.1. Fresh Concrete Properties: Workability

As per IS:6461(Part-VII)-1973 [47], "Workability is the property of fresh concrete which determines the ease and homogeneity with which concrete can be mixed, placed, compacted and finished". "Measurement of workability is a widely used empirical test mentioned by M.L. Gambhir" [48].

The mixes prepared were investigated for their workability in fresh state by subjecting them to slump test, and results obtained are shown in Figure 8.

4.2. Mechanical Properties of Concrete

The mechanical properties such as compressive strength, flexural strength and split tensile strength are tested in tested as in this study.

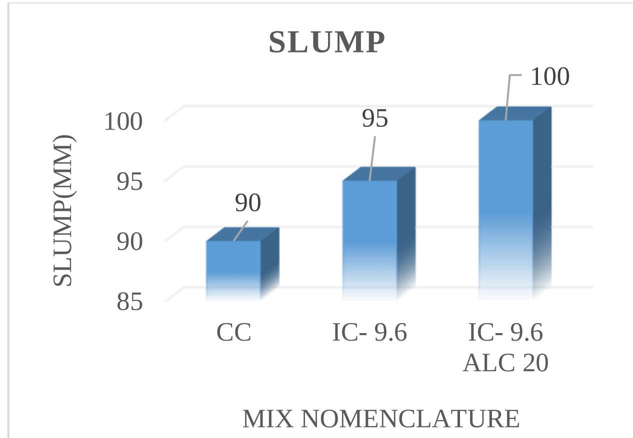

Fig. 3 Shows comparison of slump of conventionally cured concrete mix with the optimum IC mixes

4.2.1. Compressive Strength

Both CC and IC concrete cubes were tested at 28 days duration for finding out the compressive strength. The final results have been shown graphically below in Figure 9. It can be concluded that internally cured concrete gains comparable strength to the conventionally cured concrete, while the IC-9.6 ALC 20 (Alcoofine-20 % addition) gains the maximum strength of 43.10 MPa on age of 28 days, which is comparable to cc mix's strength. These results are similar to the study done by Al Saffar in 2019 [49]. Silica-fume M40 PQC strengths range 40.30–54.80 MPa at 28 days, depending on dose (Williams et al., 2022) [50], and reach ~50.9 MPa at the 10% optimum (Ammaruddin, 2025) [51]. Wood-powder-cured (internal-curing) M40 equivalents are reported by Sulaiman et al. [39] at 30.9 MPa at 5% sawdust replacement versus 21.4 MPa for the sealed control (Sulaiman et al., 2024) [39]. Hence, it can be interpreted that the internal curing concept worked in the mixes, but with lesser compressive strength, which can be increased by the addition of mineral admixture such as alcoofine.

4.2.2. Flexural Strength

In this study, a flexural strength test was done as per IS 516 (Part 1/Sec 1) [52]. At 28 days, CC's flexural strength was 7.60 MPa. The flexural strength of the IC-9.6 mix was 4.40 MPa, which is 42.11% less than that of CC. When 20% ALC was added, the flexural strength increased to 5.10 MPa, which decreased the loss to 32.89% when compared to CC. This indicates that ALC helped to increase the internally cured concrete's flexural resistance.

4.2.3. Split Tensile Strength

The split tensile strength, a critical indicator of concrete's resistance to tensile stresses. CC measured a split tensile strength of 2.91 MPa after 28 days. With a value of 2.62 MPa, the IC-9.6 mix demonstrated a 9.97% decrease in comparison to CC. With a split tensile strength of 3.02 MPa, the IC-9.6 ALC 20 mix outperformed CC by 3.78%, which is shown in Figure 9 below.

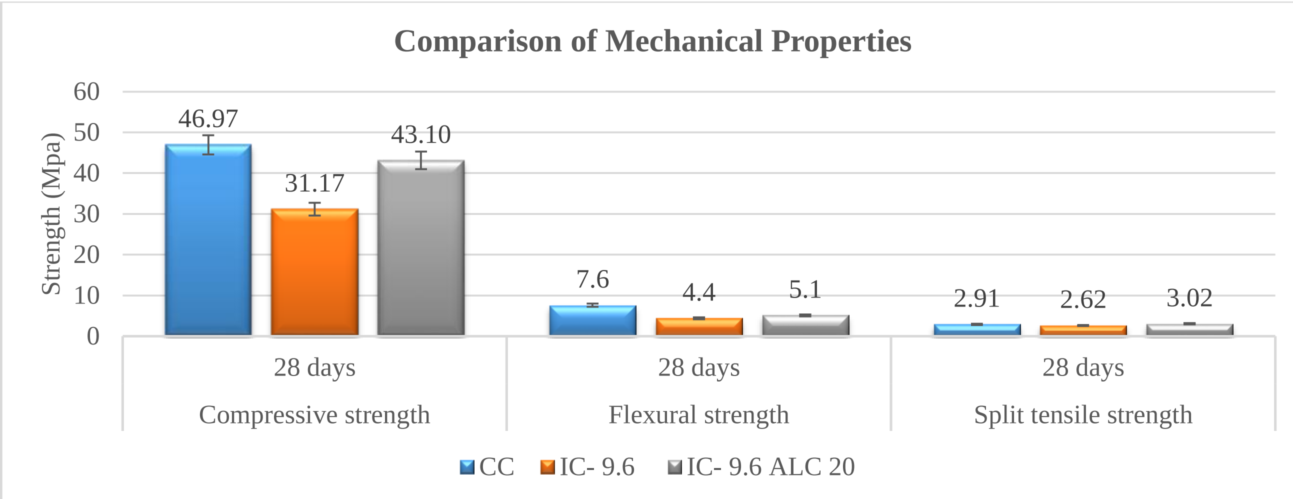

Fig. 9 Shows comparison of Mechanical properties of conventionally cured concrete mix with the different ic mixes

In the study done by at 7.5% silica fume (SF) + 15% Fly Ash (FA), the highest 28-day split-tensile strength for the M40 PQC mix was 3.60 MPa, which was 12.1% greater than the 3.21 MPa OPC control. However, a different combination of 5% SF + 10% FA produced the best compressive strength (61.50 MPa), suggesting that distinct optimal SF/FA proportions are needed for PQC mix design for compressive and tensile strengths by P, 2013 [53].

4.3. Durability Properties of Concrete

For the longer life and proper functioning throughout the life under a variety of environmental circumstances, its durability properties needs to be evaluated. So in this study, Sorptivity, permeability, water absorption, carbonation of concrete are evaluated for measuring its durability. In conclusion, choosing the right materials, designing the mix, and taking the environment into account during the course of the structure's life are all critical to obtaining great durability in concrete.

4.3.1. Sorptivity

Sorptivity test determines the durability of the concrete by measuring the rate at which water is absorbed by its sample by capillary action. In this study, the percentage of water absorption over time was measured according to ASTM C1585 [54] for the optimum mixes. The results indicated that the primary absorption (at the 6-hour mark) for the IC 9.6 mix was approximately 50%. In comparison, the secondary absorption for this mix was also nearly 45% of the total water absorption observed in the CC mix. This suggests that the IC 9.6 mix has a similar absorption behaviour, highlighting its comparable performance in terms of water absorption characteristics. While the IC 9.6 ALC 20 mix exhibited more sorptivity results, as shown in Figure 10. The inclusion of SCMs significantly influenced sorptivity. Alccofine appears to limit this increase because of its high reactivity, although have better pore refinement, evident from the FESEM images. These findings highlight the importance of mix design in managing moisture ingress in concrete.

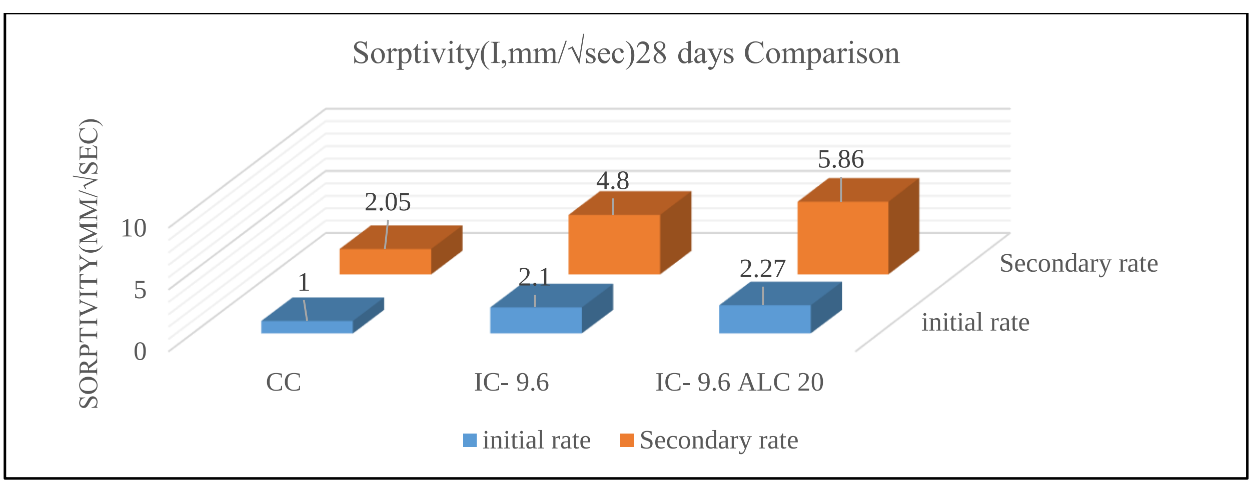

Fig. 10 Comparison of sorptivity of CC and IC 9.6 and IC 9.6 ALC-20 at 28 days

4.3.2. Density

Density is a very important parameter for measuring the concrete's strength and durability, its overall quality. In this study, it was found that the density of CC mix over the time duration of 28 days improved, while the density of the IC mix improved lesser than the CC mix may be due to light weight nature of wood powder. The density comparison graph shown in Figure 11 illustrates the variation in concrete mix densities over 3, 7, and 28 days, revealing important insights into the effect of internal curing and mineral admixtures.

The CC mix exhibited the highest density, reaching 2378.78 kg/m³ at 3 days, indicating a relatively compact matrix. The IC-9.6 and IC-9.6 ALC 20 mixes showed slightly lower densities due to the incorporation of pre-wetted wood powder, which introduced additional internal porosity. The IC-9.6 ALC 20 mix showed a slight increase in density up to 7 days, followed by a gradual decrease to 2323.95 kg/m³, indicating a relatively stable and balanced density pattern throughout hydration.

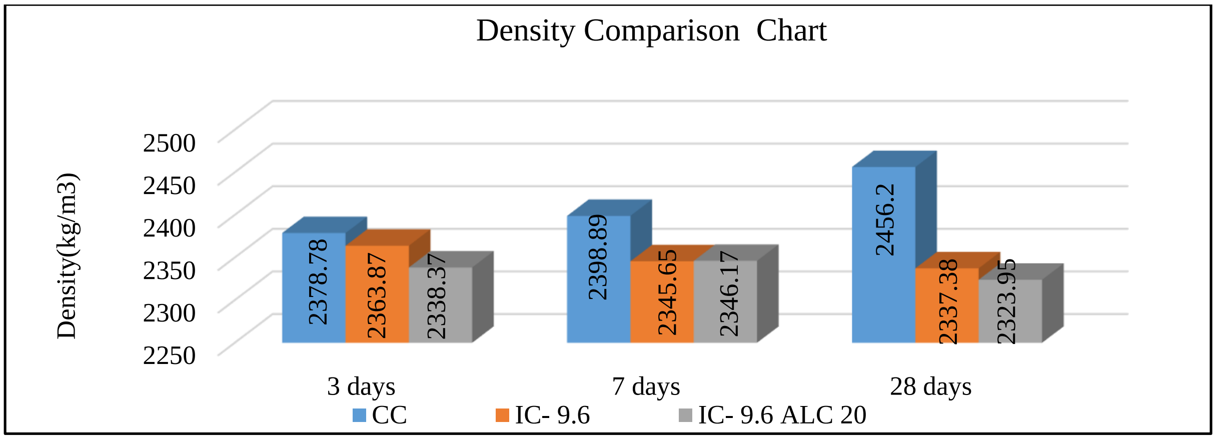

Fig. 11 Comparison of density of CC and IC Mixes

5. Micro Testing Data

5.1. FESEM Testing

A high-resolution imaging method called Field Emission Scanning Electron Microscopy (FESEM) is used to examine the microstructure of concrete in order to confirm the outcomes of numerous conventional tests.

It provides detailed insights into pore structure, hydration products, and interfacial transition zones, which are critical for understanding material nature from within. In this study, FESEM was done in order to understand the behaviors of the concrete mixes made.

5.1.1. 28 Days Testing

This test was done over a 28 days and 90 days duration on important mixes like CC Mix, IC -9.6 Mix and IC -9.6 blended with mineral admixtures mixes. Figure 12 shows the FESEM images of (a) Control Concrete (CC), (b) Internally Cured Concrete with 9.6% curing agent (IC 9.6), and (c) Internally Cured Concrete with 9.6% curing agent and 20% ALC (IC 9.6 ALC 20) at 10,000× magnification.

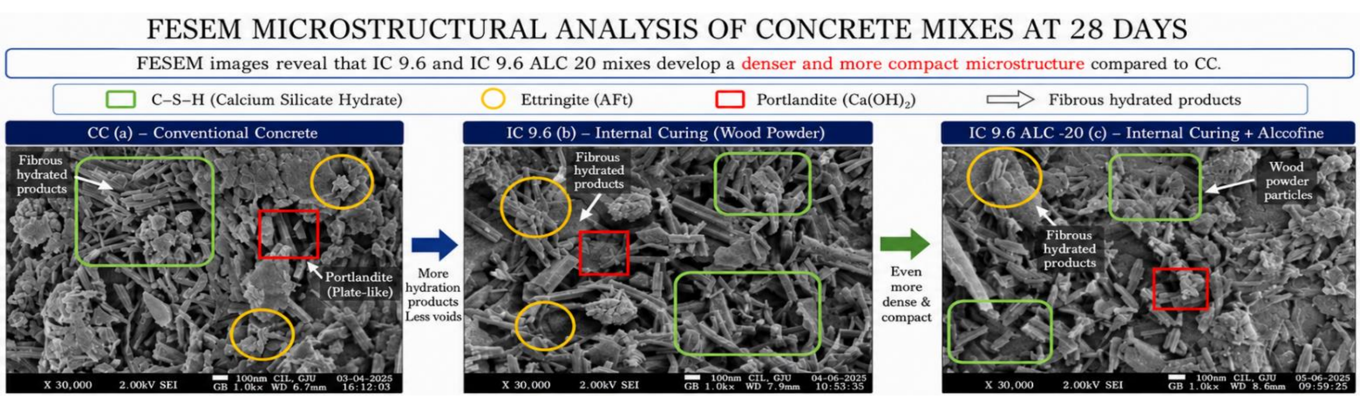

Fig. 12 Comparison of FESEM images of CC and IC 9.6 and IC 9.6 ALC -20 at 28 days

The CC sample shows relatively dense but less hydrated microstructure with unreacted cement particles. IC 9.6 exhibits enhanced formation of fibrous C-S-H due to improved hydration. The IC 9.6 ALC 20 sample presents the densest matrix with well-developed C-S-H gel and reduced porosity, indicating superior hydration and microstructural refinement due to combined internal curing and ALC inclusion. A similar pattern of gaining strength by internally cured concrete has been observed in the study.

5.1.2. 90 days Testing

Shapes shown in Figure 13 (a) below, such as a circle represents Portlandite, square represents CSH, rectangle with arched edges represents Ettringite. The 90 days duration sample analysis of both CC and IC concrete mixes provides a comprehensive understanding of the microstructure. Similar to 28 days duration results, the control concrete (CC) exhibits significant voids and hydrated cement particles, indicating poor hydration.

The IC 9.6 ALC-20 sample demonstrates a compact and homogeneous microstructure with minimal voids and a denser distribution of hydration products, confirming the positive influence of ALC on hydration and microstructural integrity. This is in line with previous research done by the [55].

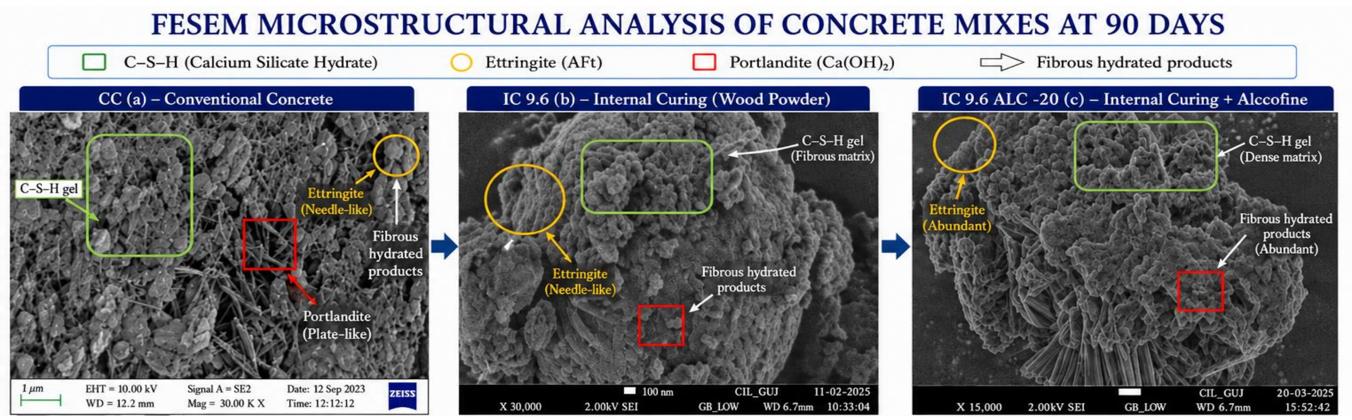

Fig. 13 Comparison of FESEM images of CC and IC Mixes at 90 days

5.1.3. Summary of Micro-Investigations

SEM analysis after 28 days shows that IC 9.6 and IC 9.6 ALC 20 mixes have enhanced hydration compared to control concrete. IC 9.6 forms more fibrous C-S-H, while IC 9.6 ALC 20 shows the densest matrix with refined microstructure and reduced porosity, indicating superior performance in 28 days' duration mixes. While at 90 days, IC 9.6 ALC-20, exhibits dense microstructures and enhanced hydration. Compared to control concrete, these mixes show reduced porosity, better ITZ development, and superior C-S-H formation, indicating improved durability and strength. Among the tested contents, 9.6% wood powder was found to be the optimum dosage, producing the most efficient hydration and crystalline phase development. Further enhancements were observed when 9.6% wood powder was combined with Alccofine, leading to superior performance at both 28 and 90 days. These combinations reduced unreacted cement and CH content while increasing C-S-H formation and transforming amorphous phases into stable crystalline hydration products.

6. Finite Element Modelling (FEM) -

The following calculations were carried out using Westergaard's edge stress Equation to determine the peak edge stresses for Conventional Concrete (CC) and Internally Cured (IC 9.6 ALC 20) pavement slabs. The parameters considered are as follows:

6.1. Input Parameters

- Slab thickness (h) = 235.5 mm = 0.2355 m
- Poisson's ratio (μ) = 0.15
- Elastic modulus (E):
  - CC slab = 34,267 MPa = 34,267 × 10^6 N/m²
  - IC 9.6 ALC 20 slab = 32,800 MPa = 32,800 × 10^6 N/m²
- Subgrade modulus (k) = 50.3 MN/m³ = 50.3 × 10^6 N/m³
- Critical location (x) = 0.15 m (from both edge)
- Wheel loads; as per IRC-58: 2015 [56]: Single axle = 10.2 t = 10,200 kg = 10,200 × 9.81 ≈ 100,062 N.
- Boundary condition- Base of slab is fixed, and corner were held down.

Similarly, for the internally cured slab IC 9.6 ALC 20, the compressive strength obtained from experimental testing was 43.10 MPa. The corresponding modulus of elasticity and shear modulus were calculated using the same set of Equations and shown in the table 3.

The slabs were subjected to wheel loading as per the provisions of IRC: 58–2015 [56]. The critical load positions were considered at a distance of 0.15 m (15 cm) from both the longitudinal and transverse slab edges to simulate maximum edge stresses. The following standard axle load configurations were applied: Single axle load = 10.2 tons. The wheel contact pressure was computed by distributing the load over the contact area, assuming a standard tyre pressure of 0.8 MPa.

Table 3. Material properties assigned to FEM slab models

Slab Model	Compressive Strength, fck (MPa)	Modulus of Elasticity, EE (MPa)	Shear Modulus, GG (MPa)	Poisson's Ratio,μ\mu
CC Slab	46.97	34,267	14,898	0.15
IC 9.6 ALC 20 Slab	43.10	32,800	14,260	0.15

6.2. Post Processing and Results

The FEM analysis was post-processed to extract the stress contours and deflection profiles for both slab models. The maximum tensile stresses were observed at the slab corners and near the edges (15 cm from both edges) under the applied critical loads. The stress contours for CC and IC 9.6 ALC 20 slabs under different loading conditions are presented in the Figures 14- 15.

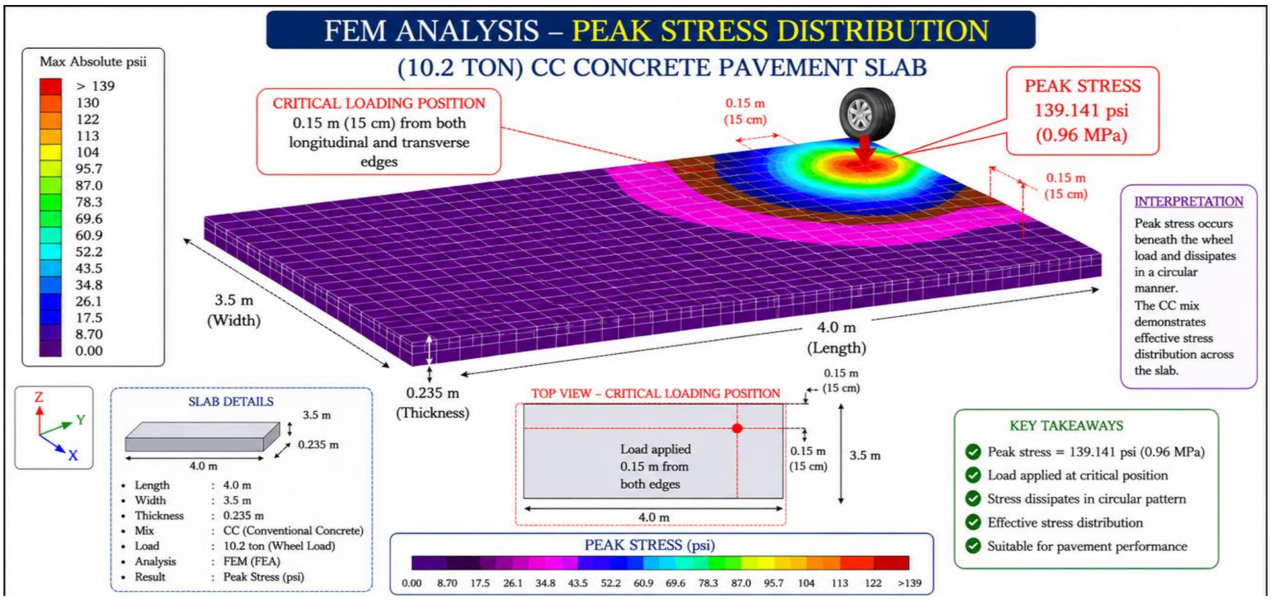

Fig. 14 Illustration of Contour stress profile of CC concrete pavement slab for 10.2 ton loading

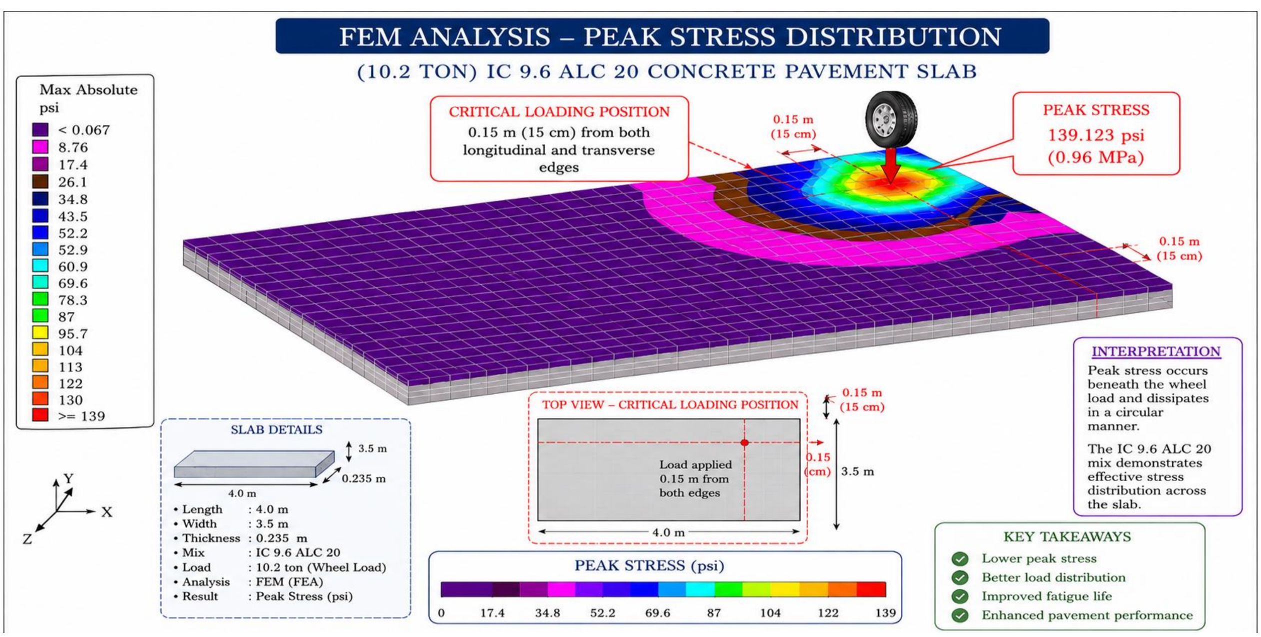

Fig. 15 Illustration of Contour stress profile of IC 9.6 ALC-20 concrete pavement slab for 10.2 ton loading

Figure 14 shows the peak stress for CC concrete pavement slab for 10.2 ton loading having a magnitude of 139.141 (psi). Peak stresses obtained in IC 9.6 ALC-20 concrete pavement slab for 10.2 are lesser than stresses obtained in conventional pavement slab.

Figure 15 shows the Contour stress profile of IC 9.6 ALC-20 concrete pavement slab for 10.2 ton loading. The value of peak stress obtained is 139.123 psi on applying loading of 10.2 ton respectively.

After calculation, the value of corner stress was also reported in table 4 below

Table 4. Corner stress values obtained from the FEM Modelling

Load Case	CC Slab (psi)	IC 9.6 ALC 20 Slab (psi)	% Reduction (IC vs CC)
Single Axle	139.142	139.123	0.014%

The stress value of IC 9.6 ALC 20 Slab is almost near to the stress obtained stress value of CC and hence maintains a structural response comparable to that of the conventional concrete slab.

7. Verification of the FEM Modelling Results by Westergaard Theory

The following calculations were carried out using Westergaard's edge stress Equation to determine the peak edge stresses for Conventional Concrete (CC) and internally cured (IC 9.6 ALC 20) pavement slabs. The parameters considered are as follows: Wheel loads: Single axle = 10.2 tons.

7.1. Input Parameters

- Slab thickness (h) = 235.5 mm = 0.2355 m
- Poisson's ratio (μ) = 0.15
- Elastic modulus (E):
- CC slab = 34,267 MPa = $34,267 \times 10^6$ N/m²
- IC 9.6 ALC 20 slab = 32,800 MPa = $32,800 \times 10^6$ N/m².
- Subgrade modulus (k) = 50.3 MN/m³ = 50.3×10^6 N/m³
- Critical location (x) = 0.15 m (from both edge)
- Wheel loads (IRC:58–2015) [56]:
- Single axle = 10.2 t = 10,200 kg = 10,200 × 9.81 ≈ 100,062 N.

7.2. Radius of Relative Stiffness (ℓ)

Radius of relative stiffness is given by Equation 3, as under-

Formula for $\ell = \left[\frac{Eh^3}{12k(1-\mu 2)}\right]^{0.25}$ (3)

- For CC slab ($E = 34,267 \times 10^6$ N/m²):

$$\ell = \left[\frac{34,267 \times 10^6 \times 0.235^3}{12 \times 50.3 \times 10^6 \times (1-0.15^2)}\right]^{0.25} = 0.931\text{m}$$

- Similarly, for IC 9.6 ALC 20 slab ($E = 32,800 \times 10^6$ N/m²): ℓ=0.923m
- CC slab → ℓ = 0.931 m
- IC 9.6 ALC 20 slab → ℓ = 0.923 m

7.3. Calculation of the Radius of Contact Area (a) using given Inputs

Step 1: Convert axle load to wheel load
Axle load = 10.2× 9.81 = 100.06 kn
Wheel load, P = 100.06/2 = 50.03 kn= 50,030N

Step 2: Calculate basic radius of contact area

$$a_o = \sqrt{(\frac{P}{\pi p})} = a_o = \sqrt{(\frac{50,030}{\pi \times 0.8})} = 141.1 \text{ mm}$$

Step 3: Check IRC 58 thickness criterion

$$\text{Check } -1.724 \times h = 1.724 \times 235.5 = 406.1 \text{ mm}$$

Since: $a_o = 141.1 < 406.1$

Step 4: Calculate modified radius of contact (IRC 58:2015)

$$a = \sqrt{(1.6 \times 235.5^2 + 141.1^2)} :$$

Finally, a = 330 mm

7.4. Westergaard theory Corner Stress Calculation

Formula (15 cm away from both edges) for finding the corner stress given is as follow:

$$\sigma_c = \frac{3P}{h^2}\left[1 - (\frac{a\sqrt{2}}{l})^{0.6}\right] \quad (4)$$

Where

- P = wheel load (N),
- h=0.2355 m,
- x=0.15 m
- ℓ = 0.931 m (CC) or 0.923 m (IC)
- a= 0.330 mm

By putting all required inputs for CC Pavement in the above Equation 4 as shown below-

$$\sigma_c = \frac{3 \times 50030}{0.235^2}\left[1 - (\frac{0.330\sqrt{2}}{0.933})^{0.6}\right] = 919880.639 \text{ N/m2}$$

If it is converted into psi, then it is to multiply it with 0.000145, as 1N/m2=0.000145psi

$$\sigma_c = 919880.639 \text{ N/m2} \times 0.000145 = 133.38 \text{ psi.}$$

7.5. Comparison of Westergaard Theory Result with the FEM Modelling Results

Results from both theory and model were analyzed and compared in table 5 for conventional Cement Concrete (CC) slabs and IC 9.6 ALC-20 slabs under single, tandem, and tridem axle loading conditions, with explicit comparison of stress magnitudes and percentage differences. For FEM modelling, the CC slab developed stresses of 139.142 psi under single axles, while the corresponding stresses in the IC 9.6 ALC-20 slab were 139.123 psi. This represents a marginal stress reduction of approximately 0.01% for single axle loading when IC 9.6 ALC-20 is used instead of conventional CC. Although numerically small, this consistent reduction indicates slightly improved load distribution and stiffness characteristics of the IC 9.6 ALC-20 slab, which can positively influence fatigue performance over the design life. A similar trend is observed in the results obtained using Westergaard theory. The stresses in the CC slab were 138.28 psi for single axles, whereas the IC 9.6 ALC-20 slab showed reduced stresses of 137.70 psi. For the CC slab, FEM stresses are higher than Westergaard stresses by approximately 0.62% for single axle loading (139.142 psi vs. 138.28 psi). For the IC 9.6 ALC-20 slab, FEM stresses exceed Westergaard predictions by about 1.03% for single axle (139.123 psi vs. 137.70 psi. These differences highlight the conservative nature of FEM modelling, which captures three-dimensional stress distribution, slab–foundation interaction, and boundary effects more realistically than the simplified Westergaard analytical approach. Compared to FEM results, the Westergaard-based analysis shows slightly higher relative stress reduction between the two slab types, reinforcing the observation that IC 9.6 ALC-20 offers marginal but consistent structural advantages under different axle configurations.

Table 5. Comparison of FEM Modelling stress results with Westergaard theory stress results

	Load Case	Single Axle
FEM Modelling	CC Slab (psi)	139.142
	IC 9.6 ALC-20 Slab (psi)	139.123
Westergaard theory	CC Slab (psi)	138.28
	IC 9.6 ALC-20 Slab (psi)	137.70

Overall, the close agreement between FEM and Westergaard results, combined with the consistently lower stresses observed in IC 9.6 ALC-20 slabs, supports the reliability of the analytical approach for preliminary design while demonstrating the advantage of FEM for detailed mechanistic evaluation and the potential performance benefits of improved concrete mixes in rigid pavement applications.

8. Fatigue Life Calculation on the Basis of Stress Ratio

8.1. Definitions and Inputs

- Stress Ratio: SR=$\frac{\sigma}{Fcr}$ (IRC:58–2015) [56].
- Where σ = critical tensile flexural stress (MPa) and Fcr = design flexural strength (modulus of rupture) (MPa).
- Fatigue life N (allowable number of equivalent axle repetitions at that stress level) is determined from IRC: 58–2015 rules-
- If SR<0.45⇒ N=∞ (i.e., allowable repetitions are infinite; the fatigue limit).
- If 0.45≤SR≤0.55, than allowable repetitions N are given by:

$$N=\left[\frac{4.2577}{SR-0.4325}\right]^{3.268}$$

- If SR>0.55, use:

$$log_{10}N=\frac{0.9718-SR}{0.0828}$$

These IRC formulations are the same fatigue relationships used in PCA-based rigid pavement design methods.

8.2. Calculation of Stress ratio (SR) values

The stress ratio value is calculated for the CC mix and IC 9.6 ALC 20 mix using the flexural strength obtained from the experimental results. The SR value is calculated by using formula as per Equation 5

$$\textit{Stress ratio (SR)} = \frac{Maximum\ flexural\ stess,\sigma(Mpa)}{Flwxural\ strength,Fcr(Mpa)} \quad (5)$$

Table 6. Calculation of stress ratio on basis of flexural strength obtained

Sr .no	Mix name	Maxi flexural stress (Mpa), σ	Flexural Strength (Mpa), Fcr	Stress ratio (SR)
1	CC	2.30	7.60	0.30
2	IC 9.6 ALC 20	2.30	5.17	0.44

The stress ratio obtained from Equation 5 are given above, and the results are compared in the table 6 given above. The value of stress ratio comes out to be 0.36 for CC mix and 0.44 for the IC 9.6 ALC 20 mix.

For CC mix: SR_{CC}=0.30
If SR_{CC}=0.30<0.45, by [56] rule, than allowable repetitions NCC=∞

For IC 9.6 ALC 20 mix: SR_{IC}=0.44
SR_{IC} =0.44<0.45, by [56] rule, than allowable repetitions NIC=∞

8.2.1. Miner's cumulative damage check

Even when an axle group has a finite N, IRC uses Miner's Rule to accumulate damage across axle groups:

For each axle group i: damage fraction $D_i=\frac{n_i}{N_i}$

Where n_i = expected (design) repetitions of axle group over design life, and N_i = allowable repetitions for that stress level (from the SR-based equations).

8.2.2. Cumulative Damage

Cumulative fatigue damage is given by the dividing expected repetitions of axle group over design life by the allowable repetitions for that stress level given in Equation 6 below

$$CFD=\sum_i \frac{n_i}{N_i} \qquad (6)$$

As per above Equation 6, given above, if the value of CFD≤1.0 than the design passes.

Now, as value of stress ratio for both CC and IC mix is IC 9.6 ALC 20 is less than 0.45, hence allowable repetitions N = ∞, so the value of CFD comes out to be 0, which is given below in table 7.

Table 7. Short summary table of cumulative damage calculation

Mix	SR	IRC Rule	Allowable repetitions N	Result for Miner sum (per axle group)
CC	0.35	SR<0.45⇒N=∞	$N_{CC}=\infty$	ni/Ni for CC=0 → No fatigue damage from axle-loading (CFD contribution = 0)
IC 9.6 ALC 20	0.44	SR<0.45⇒N=∞	$N_{IC}=\infty$	ni/Ni for IC=0 → No fatigue damage from axle-loading (CFD

8.2.3. Discussion of Results of Fatigue life

Since both $N_{CC}=\infty$ and $N_{IC}=\infty$, each ni/Ni = 0 and therefore CFD = 0 (for fatigue due to axle load flexural stresses alone), i.e., the SR-based fatigue check is satisfied trivially for any finite traffic volume. Practically, this means fatigue cracking due to repeated axle flexural stresses is not the governing failure mode for either mix under the given SRs.

9. Economic Analysis of Concrete Pavement Slabs

An economic evaluation was carried out for the material cost to compare the cost efficiency of Conventional Concrete (CC), Internally Cured Concrete (IC 9.6), and internally cured concrete with artificial lightweight coarse aggregates (IC 9.6 ALC 20). The cost analysis was performed on a per cubic meter basis using the unit rates of constituent materials as shown above in table 8. The unit rate of each item is taken from the current market rate on commercial basis. Unit rate for material such as cement, sand, aggregates are taken in kg, while the unit for materials such as admixture, water is taken in liters. Here the only the construction material cost is considered, labor cost, other miscellaneous expenditures for construction of slab are not considered in this economic analysis. Detailed analysis of each design mix and material is given in table 8.

Rate of water for curing is taken as Rs. 5/liter (Rs 4 plus additional charges, commercial rate) is taken from the commercial water charges rate list published by the urban local bodies, Public Health Engineering Department, Haryana, through an order dated March 9, 2011, in the Haryana govt. Gazette (extra) [57].

Table 8. Calculation of cost of material for the pavement construction for CC mix, IC 9.6 mix and IC 9.6 ALC 20 mix

Cost Comparison								
Sr. no	**Mix constituents**	**CC (Kg/m3)**	**Tentative Cost (CC)**	**IC 9.6 (Kg/m3)**	**Tentative Cost (IC-9.6)**	**IC 9.6 ALC 20 (Kg/m3)**	**Tentative Cost (IC-9.6 ALC 20)**	**Unit Rate (per kg/liter)**
1	Cement	415.00	3735.00	415.00	3735.00	415	3735	9
2	Flyash	90.00	540.00	90.00	540.00	90	540	6
3	Mineral Admixture	0.00	0.00	0.00	0.00	83	2075	25
3	C.A.(20mm)	655.00	1310.00	655.00	1310.00	655	1310	2
4	C.A.(10mm)	560.00	1120.00	560.00	1120.00	560	1120	2
5	Sand	655.00	1965.00	591.62	1774.87	591.622	1774.866	3
6	Water	180.00	900.00	180.00	900.00	178	890	5
7	Admixture	8.35	1252.50	8.35	1252.50	8.27	1240.5	150
8	IC Agent (Wood Powder)	0	0.00	63.378	126.76	63.378	126.756	2
9	Curing Cost	3000	15000.00	128	640.00	128	640	5
10	Total amount/m3 (Rs.)		25822.50		11399.12		13452.122	

11	Conc. Volume per km		822.5		822.5		822.5	
12	Cost per km		21239006.25		9375777.845		11064370.35	
13	% Difference		0		-55.86		-47.91	
* All quantities of mix constituents are measured in kilograms (kg)								

Quantity of water for external curing CC concrete mix is taken 3000 liters because as each 1 m^3 of making of concrete requires around 3 m^3 of water during construction, mostly used for curing [13]. Quantity of water for internal curing in IC 9.6 and IC 9.6 ALC 20 is taken as 128 liter/m^3, because water for the curing was given by the prewetted wood powder, which has approx 2 times water absorption capacity (derived experimentally and detail given in wood powder section of this study). So water absorbed for curing = Mass of wood powder used in the mix (kg/m^3) × water absorption capacity = 63.378×2= 128 liter/m^3.

Per unit cost of each ingredient is given in last column of table 8. Quantities of each ingredient of all three mixes is taken as per their respective design mix (detail given in design mix section). Quantity each mixes are than multiplied by their unit rate, and total cost per cubic meter is found and compared. For the conventional concrete slab, the cost was estimated at ₹25,822.50/m³, whereas the IC 9.6 mix and IC 9.6 ALC 20 mix recorded costs of ₹ 11,399.12/m³ and ₹ 13,452.12/m³, respectively. The results clearly indicate that the internally cured mixes achieved significant cost reductions, with IC 9.6 being the most economical option.

9.1. Pavement Material Cost Estimation per Kilometer

For practical implementation, the per cubic meter cost was extrapolated to estimate the total cost of material for constructing a one-kilometer-long concrete pavement slab. Considering a standard single-lane slab of 3.5 m width and 0.235 m thickness, the concrete volume required per kilometer length is:

Volume=Length × Width × Thickness
Volume =1000 m×3.5 m×0.2355 m≈ 824.25 m^3
Accordingly, the total cost for each pavement type is:

- CC pavement = 824.25 × 25,822.50 ≈ ₹ 2.129 crore
- IC 9.6 pavement = 824.25 × 11,399.12 ≈ ₹ 0.939 crore
- IC 9.6 ALC 20 pavement = 824.25 × 13,452.12 ≈ 1.109 crore

9.2. Comparative Analysis

Figure 16 shows the graphical comparison of the cost of pavement construction per km of all three mixes. Although this is the cost of only the material, labor cost is not added in it. The economic analysis highlights a substantial cost saving of 55–48% when using internally cured mixes compared to conventional concrete. Among the alternatives, IC 9.6 mix emerges as the most cost-effective option, offering more than ₹ 1.18 crore savings per kilometer of pavement length. The IC 9.6 ALC 20 mix saves approximately 1.01 crore cost of the material than cc. Although The IC 9.6 ALC 20 mix, while slightly costlier than IC 9.6, still demonstrates significant savings over the conventional mix, along with the added benefits of improved internal curing and potential durability enhancements. Thus, the results strongly support the adoption of internally cured systems for large-scale pavement construction, ensuring both economic feasibility and improved performance.

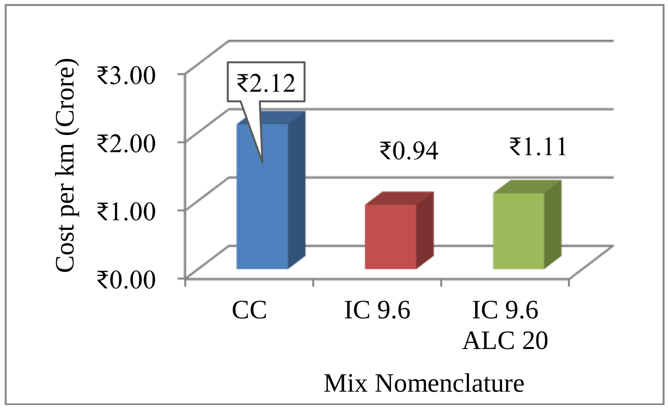

Fig. 16 Graphical cost comparison of PQC concrete per km of CC, IC-9.6 and IC- 9.6 ALC 20

10. Results and Discussion of using Fine Wood Powder in Concrete

- Wood powder can be effectively incorporated into concrete to produce lightweight internally cured concrete due to its low specific gravity (0.40) and very high water absorption capacity (≈200%), coupled with effective water desorption.
- The Internally Cured (IC) mixes achieved strength levels comparable to Conventionally Cured (CC) concrete, with the highest compressive strength observed for IC-9.6 ALC 20 (43.10 MPa at 28 days), and the inclusion of mineral admixtures further enhanced compressive strength across the mixes.
- IC concrete exhibited slower flexural strength development, it reached about 58% of CC strength by 28 days, while IC-9.6 ALC 20 performed better, attaining approximately 67.10% of the CC flexural strength at the same age.
- The CC mix exhibited the highest density gain over 28 days, while IC mixes showed comparatively lower gains, with IC-9.6 ALC 20 achieving the highest density (2323.95 kg/m³) among the mineral admixture blends.
- Sorptivity increased with internal curing and SCMs, while Alccofine (IC-9.6 ALC 20) demonstrated relatively

lower values of both parameters, indicating better pore refinement and moisture resistance.

- The FEM study suggested that internally cured concrete pavement slabs can achieve structural performance comparable to conventional slabs. The lesser edge stresses and improved deflection control indicate potential benefits for enhancing service life and reducing early-age cracking in concrete pavements.
- The economic analysis exhibited that internally cured concrete mixes gains 48–55% cost savings as compared to conventional concrete, with the IC 9.6 mix offering the highest savings of over ₹1.1 crore per kilometre. Although IC-9.6 (ALC 20) is little costlier than IC 9.6 Mix (i.e.-) but still much more cheaper than CC mix.
- Hence, internally cured concrete exhibited comparable strength to conventionally cured concrete, self-cured, economically viable and durable option for large-scale pavement construction.

11. Conclusion

This study presents wood powder as a sustainable internal curing agent for pavement quality concrete, by its low specific gravity =0.40 and its high water absorption near to 200% and controlled desorption capacity, thereby enhancing cement hydration and mitigating early-age moisture deficiency. Among the investigated mixes, IC-9.6 and IC-9.6 ALC 20 were identified as the optimum, exhibiting comparable mechanical, durability, and microstructural characteristics compared to Conventional Concrete (CC). In particular, IC-9.6 ALC 20 achieved a compressive strength of 43.10 MPa at 28 days, alongside comparable flexural strength, indicating its suitability for pavement. Durability performance was significantly enhanced in Alccofine-blended mixes, as evidenced by reduced sorptivity, which indicates refined pore structure and improved resistance to moisture ingress. Microstructural investigations, such as FESEM, exhibited the synergistic action of wood powder and Alccofine, further transformed amorphous phases into stable crystalline structures, contributing to improved mechanical and durability performance. Structural performance evaluation using finite element modelling demonstrated that internally cured concrete pavement slabs exhibit behaviour comparable to conventional slabs, with reduced edge stresses, which is further validated by the Westergaard analysis. No. of the repetition came out to be infinite for all mixes in fatigue life calculation on the basis of stress ratio, which confirms the value of Cumulative Fatigue Damage (CFD) = 0.

Furthermore, the economic analysis highlighted the practical feasibility of the proposed system, revealing substantial cost savings of 48–55% compared to conventional concrete pavements. The IC-9.6 mix provided the maximum economic benefit, with savings exceeding ₹1.1 crore per kilometre, while IC-9.6 ALC 20, despite being marginally costlier than IC-9.6, remained significantly more economical than CC.

Overall, this study confirm that wood powder-based internally cured concrete is a structurally efficient, self-curing, durable, and cost-effective alternative to conventional concrete for large-scale pavement construction. These findings provide a strong foundation for further field validation and long-term performance studies, facilitating the practical adoption of internally cured concrete in rigid pavement infrastructure.

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The Author declares that there are no financial, personal, or professional conflicts of interest that could have influenced the content, decisions, or outcomes related to this work.

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References

[1] Treval C. Powers, *A Discussion of Cement Hydration in Relation to the Curing of Concrete*, Portland Cement Association, pp. 1-10, 1948. [Google Scholar] [Publisher Link]

[2] A.M. Neville, *Properties of Concrete*, 5th ed., Pearson Education, 2011. [Publisher Link]

[3] P. Kumar Mehta, and Paulo J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed., McGraw-Hill Education, 2014. [Google Scholar] [Publisher Link]

[4] D.P. Bentz, Pietro Lura, and J.W. Roberts, "Mixture Proportioning for Internal Curing," *Concrete International*, vol. 27, no. 2, pp. 35-40, 2005. [Google Scholar] [Publisher Link]

[5] Dale P. Bentz, and Jason Weiss, "*Internal Curing: A 2010 State-of-the-Art Review*," National Institute of Standards and Technology, pp. 1-82, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[6] K. Kovler, A. Souslikov, and A. Bentur, "Pre-Soaked Lightweight Fine Aggregates as Additives for Internal Curing in Concretes," *Cement, Concrete, & Aggregates*, vol. 46, no. 2, pp. 1-8, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[7] Shrinkage Cracks in Concrete: Types, Causes and Prevention, The Constructor. [Online]. Available: https://theconstructor.org/concrete/shrinkage-cracks-in-concrete-types-causes/9016/

[8] P.K Mehta, and P. J. M. Monteiro, *Durability*, Concrete, Microstructure, Properties and Materials, pp. 113-155, 1993. [Google Scholar]

[9] Mohammad Shamim Khan, and Michael E. Ayers, "Curing Requirements of Silica Fume and Fly Ash Mortars," *Cement and Concrete Research*, vol. 23, no. 6, pp. 1480-1490, 1993. [CrossRef] [Google Scholar] [Publisher Link]

[10] R. Philleo, "Concrete Science and Reality," *Materials Science of Concrete*, pp. 1-8, 1991. [Google Scholar]

[11] Ole Mejlhede Jensen, *Report 41: Internal Curing of Concrete - State-of-the-Art Report of RILEM Technical Committee 196-ICC*, RILEM Publications, pp. 1-141, 2007. [Google Scholar] [Publisher Link]

[12] T.C. Powers, L. E. Copeland, and H. W. Mann, "Capillary Continuity and Discontinuity in Cement Pastes," *Journal of the PCA Research and Development Laboratories*, vol. 1, no. 2, pp. 38-48, 1959. [Google Scholar]

[13] A.S. El-Dieb, "Self-Curing Concrete: Water Retention, Hydration and Moisture Transport," *Construction and Building Materials*, vol. 21, no. 6, pp. 1282-1287, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[14] Chennai Water Crisis Hits Construction Sector, 2019, LiveMint, 2019. [Online]. Available: https://www.livemint.com/industry/infrastructure/chennai-water-crisis-hits-construction-sector-1560943322189.html

[15] Timothy J. Barrett, Albert E. Miller, and W. Jason Weiss, "*Documentation of the INDOT Experience and Construction of the Bridge Decks Containing Internal Curing in 2013*," Report no. HWA/IN/JTRP-2015/10, Purdue University, pp. 1-108, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[16] Carmelo Di Bella et al., "*Documenting the Construction of a Plain Concrete Bridge Deck and an Internally Cured Bridge Deck*," Report, Purdue University System, pp. 1-48, 2012. [Google Scholar] [Publisher Link]

[17] John Cleary, and Norbert Delatte, "Implementation of Internal Curing in Transportation Concrete," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2070, no. 1, pp. 1-7, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[18] Internally Cured Concrete Enhances Water Tank Durability in Denver Water Projects, Arcosa Lightweight, 2026. [Online]. Available: https://arcosalightweight.com/case-studies/internal-curing/denver-water/.

[19] Sajjad Ali Mangi et al., "Utilization of Sawdust in Concrete Masonry Blocks: A Review," *Mehran University Research Journal of Engineering and Technology*, vol. 38, no. 2, pp. 487-494, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Bhavin Soni et al., "Sustainable Valorization of Wood Powder via Batch and Continuous Pyrolysis," *International Conference on Environmental Pollution and Its Control (EPIC-2019)*, Rajasthan, India, 2019. [Google Scholar]

[21] Bamidele Charles Olaiya, Mustapha Muhammad Lawan, and Kolawole Adisa Olonade, "Utilization of Sawdust Composites in Construction—A Review," *SN Applied Sciences*, vol. 5, no. 5, pp. 1-25, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] P. Paramasivam, and Y.O. Loke, "Study of Sawdust Concrete," *International Journal of Cement Composites and Lightweight Concrete*, vol. 2, no. 1, pp. 57-61, 1980. [CrossRef] [Google Scholar] [Publisher Link]

[23] A. D. Hofstrand, A. A. Moslemi, and J. F. Garcia, "Curing Characteristics of Wood Particles from Nine Northern Rocky Mountain Species Mixed with Portland Cement," *Forest Products Journal*, vol. 34, no. 2, pp. 57-61, 1984. [Google Scholar]

[24] M. Hachmi, and A. A. Moslemi, "Correlation between Wood-Cement Compatibility and Wood Extractives," *Forest Products Journal*, vol. 39, no. 6, pp. 55-58, 1989. [Google Scholar]

[25] Yi Min Wei, Yia Guang Zhou, and Bunichiro Tomita, "Hydration Behavior of Wood Cement-based Composite I: Evaluation of Wood Species Effects on Compatibility and Strength with Ordinary Portland Cement," *Journal of Wood Science*, vol. 46, pp. 296-302, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[26] S. R. Karade, M. Irle, and K. Maher, "Assessment of Wood–Cement Compatibility: A New Approach," *Holzforschung*, vol. 57, no. 6, pp. 672-680, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[27] D.P. Bentz, and K.A. Snyder, "Protected Paste Volume in Concrete: Extension to Internal Curing using Saturated Lightweight Fine Aggregate," *Cement and Concrete Research*, vol. 29, no. 11, pp. 1863-1867, 1999. [CrossRef] [Google Scholar] [Publisher Link]

[28] Paki Turgut, and Halil Murat Algin, "Limestone Dust and Wood Sawdust as Brick Material," *Building and Environment*, vol. 42, no. 9, pp. 3399-3403, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[29] O.M. Ogundipe, and Y.A. Jimoh, "Durability-Based Appropriateness of Sawdust Concrete for Rigid Pavement," *Advanced Materials Research*, vol. 62-64, pp. 11-16, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[30] Saleh I. Khassaf, Aqeel Sh. Al-Adili, and Rafid S. Rasheed, "Seepage Analysis underneath Diyala Weir Foundation Using Numerical Model," *Proceedings of the Thirteen International Water Technology Conference*, Hurghada, Egypt, pp 301-310, 2009. [Google Scholar]

[31] Yong Cheng et al., "The Implementation of Waste Sawdust in Concrete," *Engineering*, vol. 5, no. 12, pp. 943-947, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[32] Olugbenga Joseph Oyedepo, Seun Daniel Oluwajana, and Sunmbo Peter Akande, "Investigation of Properties of Concrete Using Sawdust as Partial Replacement for Sand," *Civil and Environmental Research*, vol. 6, no. 2, pp. 35-42, 2014. [Google Scholar] [Publisher Link]

[33] F.A. Olutoge et al., "Investigations on Sawdust and Palm Kernel Shells as Aggregate Replacement," *ARPN Journal of Engineering and Applied Sciences*, vol. 5, no. 4, pp. 7-13, 2010. [Google Scholar] [Publisher Link]

[34] Ruhal Pervez Memon et al., "Mechanical and Thermal Properties of Sawdust Concrete," *Jurnal Teknologi*, vol. 79, no. 6, pp. 23-27, 2017. [CrossRef] [Google Scholar] [Publisher Link]
[35] Ahmad Mustafa Sabaoon, and Navinderdeep Singh, "Experimental Investigation of Self-Curing Concrete by Using Natural and Chemical Admixtures," *Indian Journal of Science and Technology*, vol. 12, no. 5, pp. 1-6, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[36] Rafat Siddique et al., "Utilization of Treated Saw Dust in Concrete as Partial Replacement of Natural Sand," *Journal of Cleaner Production*, vol. 261, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[37] Abdullah Ekinci, Mohammad Hanafi, and Ertug Aydin, "Strength, Stiffness, and Microstructure of Wood-Ash Stabilized Marine Clay," *Minerals*, vol. 10, no. 9, pp. 1-23, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[38] K. Shantveerayya et al., "Performance Evaluation of Hollow Concrete Blocks made with Sawdust Replacement of sand: Case study of Adama, Ethiopia," *International Journal of Engineering*, vol. 35, no. 6, pp. 1119-1126, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[39] Muhd Fauzy Sulaiman et al., "The Effect of Sawdust as Self-Curing Agent in Concrete," *Science and Engineering*, vol. 86, no. 3, pp. 127-133, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[40] "*IS 269:2015: Ordinary Portland Cement - Specification*," Bureau of Indian Standards, 2015. [Google Scholar] [Publisher Link]
[41] "*IS 1489-2: 1991: Specification for Portland-Pozzolana Cement, Part 2: Calcined Clay Based*," Bureau of Indian Standards, pp. 1-19, 1991. [Publisher Link]
[42] "*IS 383:2016 Coarse and Fine Aggregate for Concrete – Specification*," Bureau of Indian Standards, pp. 1-22, 2016. [Google Scholar] [Publisher Link]
[43] "*IS 1124: 1974: Method of Test for Determination of Water Absorption, Apparent Specific Gravity and Porosity of Natural Building Stones*," Bureau of Indian Standards, 1974. [Google Scholar] [Publisher Link]
[44] Ramalingam Malathy, Ill-Min Chung, and Mayakrishnan Prabakaran, "Characteristics of Fly Ash-Based Concrete Prepared with Bio Admixtures as Internal Curing Agents," *Construction and Building Materials*, vol. 262, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[45] "*IS 10262 (2009): Guidelines for Concrete Mix Design Proportioning*," Bureau of Indian Standards, pp. 1-21, 2009. [Publisher Link]
[46] William Jason Weiss, and Luca Montanari Arup, "*Guide Specification for Internally Curing Concrete*," Institute for Transportation, 2017. [Google Scholar] [Publisher Link]
[47] "*IS 6461-7 (1973): Glossary of Terms Relating to Cement Concrete, Part 7: Mixing, Laying, Compaction, Curing and Other Construction Aspects*," *Bureau of Indian Standards*, pp. 1-35, 1973. [Publisher Link]
[48] Murari Lal Gambhir, *Concrete Technology: Theory and Practice*, McGraw-Hill Education, pp. 1-774, 2013. [Google Scholar] [Publisher Link]
[49] Doha M. Al Saffar, Aymen J.K. Al Saad, and Bassam A. Tayeh, "Effect of Internal Curing on Behavior of High-Performance Concrete: An Overview," *Case Studies in Construction Materials*, vol. 10, pp. 1-14, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[50] Kanmalai Williams et al., "A Study on the Mechanical Properties of Green Concrete," *Civil Engineering Journal*, vol. 8, no. 5, pp. 1011-1028, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[51] Mohd. Ammaruddin et al., "Experimental Study on the Effect of Silica Fume on Strength and Durability of M40 Grade Ready Mix Concrete," *International Journal for Research in Applied Science and Engineering Technology*, vol. 13, no. 11, pp. 2161-2165, 2025. [CrossRef] [Publisher Link]
[52] "*IS 516 (Part 1/Sec 1):2021 Hardened Concrete - Methods of Test: Part 1 Testing of Strength of Hardened Concrete: Section 1 Compressive, Flexural and Split Tensile Strength, Flexural and Split Tensile Strength*," Bureau of Indian Standards, 2021. [Google Scholar] [Publisher Link]
[53] P. Magudeaswaran, and P. Eswaramoorthi, "Experimental Investigations of Mechanical Properties on Micro silica (Silica Fume) and Fly Ash as Partial Cement Replacement of High Performance Concrete," *IOSR Journal of Mechanical and Civil Engineering*, vol. 6, no. 4, pp. 57-63, 2013. [CrossRef] [Google Scholar] [Publisher Link]
[54] *ASTM C1585-20: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes*, ASTM International, pp. 1-6, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[55] Bhanavath Sagar, and M.V.N. Sivakumar, "Mechanical and Microstructure Characterization of Alccofine based High Strength Concrete.," *Silicon*, vol. 14, no. 3, pp. 795-813, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[56] Kama Koti Marg, *IRC:58-2015: Guidelines for the Design of Plain Jointed Rigid Pavements for Highways (Fourth Revision)*, Indian Roads Congress, pp. 1-104, 2015. [Google Scholar]
[57] "*Public Health Engineering Department Haryana*," Water Charges Notification, Haryana Government Gazette, 2011. [Publisher Link]